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1 Direct Numerical Simulation of Flow Instabilities over
2 Savonius Style Wind Turbine Blades

3 A. Ducoin¹, M. S. Shadloo² and S. Roy³

4 ¹ *LHEEA laboratory, Ecole Centrale de Nantes (CNRS UMR 6598), 44300 Nantes,*
5 *France*

6 ² *CORIA Laboratory-UMR 6614, CNRS-University & INSA of Rouen, 76000, Rouen,*
7 *France*

8 ³ *IRPHE Laboratory UMR 7342, Aix Marseille University, France*

9 **Abstract**

10 In this paper, Direct Numerical Simulations (DNS) are carried out in order
11 to capture the flow instabilities and transition to turbulence occurring on a
12 Savonius style wind turbine (SSWT) blade. Simulations are conducted with
13 the open source code NEK5000, solving the incompressible Navier-Stokes
14 equations with a high order, spectral element method. Because of the rela-
15 tively high Reynolds number considered ($Re_\xi = 9 \times 10^4$), the computational
16 domain of the Savonius blade is reduced to the pressure side, and the blade
17 is studied in static condition, which avoids the large scale vortex shedding
18 that occurs on its suction side, particularly allows to investigate the static
19 performance of the wind turbine. The results suggest that Görtler vortices
20 can occur and cause the flow to transit to turbulence, which modify the pres-
21 sure and wall friction distributions, and consequently alter the drag and lift
22 forces.

23 *Keywords:* Direct Numerical Simulation, Savonius Style Wind Turbine,
24 centrifugal instability, blade performance

*

¹antoine.ducoin@ec-nantes.fr

25 1. Introduction

26 The objective of this paper is to investigate the flow instability over the
27 pressure side of a Savonius style wind turbine (SSWT). Although, the wind
28 energy market has been dominated by the horizontal axis wind turbines
29 (HAWTs); recently, vertical axis wind turbines (VAWTs) are also finding
30 emerging interest for off-grid applications ([1, 2]). As have been reported in
31 the literature [3], the VAWTs possess a number of distinct advantages over
32 HAWTs such as easy installation and maintenance, less installation space,
33 self-starting at low wind speeds, wind acceptance from any direction, no need
34 of yaw mechanism, easy fabrication, and less noise among others.

35 SSWT, as a member of VAWTs, appears to be promising for off-grid
36 energy conversion because of its better self-starting capability and flexible
37 design promises [4]. SSWT blades are characterized by relatively large sur-
38 faces, which are thin circular shape to produce large drag for power gen-
39 eration. Typically, the suction side of the advancing blade is submitted to
40 strong adverse pressure gradient, causing a well known vortex shedding pro-
41 cess, which is responsible for the wake flow. This topic has been the subject
42 of many researches in the past decades, as it obviously depends on tip speed
43 ratio (TSR) and directly influences the turbine efficiency [5, 6]. The flow on
44 the pressure side of the blade is generally considered as fully attached and is
45 characterized by high pressure, low velocity level that produces most of the
46 drag used in the energy conversion. However, because of the gap between
47 the two blades, the flow is accelerated on the pressure side of the returning
48 blade and a thicker boundary layer develops at this side. Because of the
49 concave curvature of the blade and the small scale of the turbine, centrifugal

50 instabilities (pairs of longitudinally elongated counter rotating vortices) may
51 occur; and depending on the flow characteristics, can cause natural transi-
52 tion on the blade [7]. Moreover, these vortices induce different mechanisms
53 of ejections and sweeps, causing thereby strong transverse variations of the
54 drag coefficient, which results in the formation of hot spots near solid walls
55 (i.e. blade surface) [8]. This can also lead to a rapid degradation of mechan-
56 ical structures and materials fatigue. It has to be noted that because of the
57 small scale of these turbines, viscous effects are of the primary importance in
58 the prediction of the turbine performance, and it becomes necessary to lead
59 detailed analysis of the flow physic to evaluate its influence.

60 In last few decades, a number of experimental and numerical investigations
61 have been carried out on the performance analysis of SSWTs [3]. Several
62 improvements had then been performed to increase their performances, this
63 includes optimizing height to diameter ratio (aspect ratio, AR) [9], adding
64 of end plates at the top and bottom of the turbine blades that marginally
65 increases the performance [10], and several flow control systems [11]. Fur-
66 ther, it is now usual to have a certain overlap between the turbine blades to
67 accelerate the flow near the trailing edge of the advancing blade and insert
68 pressure on the suction side of the returning blade [12]. This is often reported
69 to be beneficial for the performance improvement of this turbine [13, 3]. In
70 [14], unsteady Reynolds-averaged Navier-Stokes (URANS) simulations were
71 performed over a semi circular, SSWT. The authors investigated the gap
72 flow, and concluded that a boundary layer flow occurs on the pressure side
73 of the returning blade. This is due to acceleration and re-orientation of the
74 flow generated by the gap (see Figure 1). The latter has a positive effect

75 on the turbine performance, which produces more drag. However, because
76 of the boundary layer development on the concave side of the blade surface
77 (i.e. pressure side), the flow may become unsteady due to small scale distur-
78 bances. These flow features are not captured by URANS methods that are,
79 however, still the most popular means to predict the turbine performances
80 [5, 15].

81 The case of a boundary layer flow on a curved, circular wall, is typically
82 associated with centrifugal instabilities. On such concave geometries, the
83 wall-normal balance of forces on the fluid is modified by the presence of
84 a centrifugal force, which increases away from the wall and is balanced by
85 the pressure force. Next, a sharp wall-normal displacement of fluid in the
86 boundary layer due to the surface roughness often destroys this balance and
87 destabilize the shear layer. This instability mechanism may lead laminar
88 boundary layer to transit to turbulence [16]. The phenomena of such cen-
89 trifugal instability, known as Görtler instability, is relatively well studied, as
90 numerous experimental, and more recently numerical studies have investi-
91 gated this flow [17, 18]. As observed in [18], the boundary layer instability
92 appears with counter rotating steady vortices with constant span-wise wave-
93 length, having a constant stream-wise location. As shown in [19] and [20],
94 these vortices forms together with longitudinal streaks with low and high
95 momentum because of the vertical displacement of the flow. These streaks
96 then deform the flow and the low momentum regions form the well known
97 mushroom like shapes structures [21]. Finally, it was also shown that the
98 skin friction coefficient is increased compared to flow over a flat plate be-
99 cause nonlinear modification of the primary steady flow by wavy secondary

100 instabilities [22].

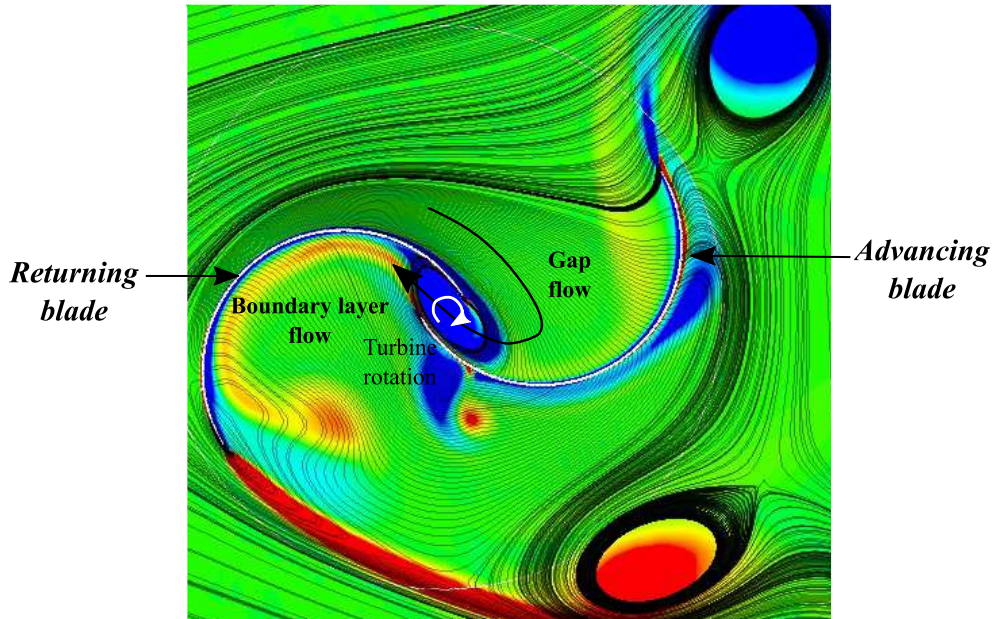


Figure 1: Vortex flow around a SSWT. URANS calculation from [14] at the tip speed ratio of $TSR=0.8$, and Reynolds number of $Re = 12.3 \times 10^4$

101 To demonstrate the presence of centrifugal instabilities on SSWTs, DNS
 102 computations are performed with the open-source spectral elements code
 103 NEK5000 [23] on the pressure side of a single blade, under a constant inflow
 104 condition with no turbine rotation. The main objectives of the present study
 105 are (i) to verify if such flow can actually occurs on SSWT blades in the range
 106 of operating Reynolds number considered for this type of turbine ($1 \times 10^5 <$
 107 $Re < 2 \times 10^5$) (ii) to investigate the modification of boundary layer flow,
 108 and hence (iii) the changes in aerodynamic performances, including friction,
 109 pressure and drag characteristics.

110 The manuscript is organized as follow: after a presentation of the numer-
 111 ical method in section 2, a mesh sensitivity analysis is presented considering
 112 the element order with the same mesh. Since the present geometry (with
 113 high tip curvature) has never been investigated in the past, the spectral el-
 114 ement method is validated with a curved wall of constant radius $R = 1\text{m}$
 115 in section 3, which is the most popular case to study centrifugal instabilities
 116 nowadays. A detailed analysis of the flow is then carried out in section 4. It
 117 is followed in the same section by the investigation of pressure, friction at the
 118 wall and drag and lift forces, which are compared with URANS simulations
 119 to highlight the contribution of the present work. Finally, the manuscript is
 120 concluded in section 5.

121

122 2. Numerical Model

123 The dynamics of a three-dimensional incompressible flow of a Newtonian
 124 fluid are described by the Navier-Stokes equations

$$\dot{\mathbf{U}} = -(\mathbf{U} \cdot \nabla)\mathbf{U} - \nabla P + Re^{-1}\Delta\mathbf{U}, \quad (1)$$

$$\nabla \cdot \mathbf{U} = 0.$$

125 Here $\mathbf{U} = (U_x, U_y, U_z)^T$ is the velocity vector, where U_x , U_y , and U_z being
 126 its component along x -, y -, and z - axes, respectively, and P represents
 127 the pressure term. The velocity is non-dimensionalized by the free-stream
 128 velocity U_∞ and the flow conditions are set according to the free-stream
 129 Reynolds number, $Re_\xi = U_\infty \xi / \nu$, where ν is the kinematic viscosity of the

130 considered fluid and ξ is the curvilinear distance between the leading edge
131 and the trailing edge.

132 Navier-Stokes equations are solved using NEK5000 flow solver developed
133 at Argonne National Laboratory [24]. It is based on the spectral elements
134 method (SEM), introduced in [25], which provides spectral accuracy in space
135 while allowing for the geometrical flexibility of finite element methods. Spa-
136 tial discretization is obtained by decomposing the physical domain into spec-
137 tral elements within which the velocity is defined on Gauss-Lobatto-Legendre
138 (GLL) nodes and the pressure field on Gauss-Legendre (GL) nodes. The solu-
139 tion to the Navier-Stokes equations is then approximated within each element
140 as a sum of Lagrange interpolants defined by an orthogonal basis of Legendre
141 polynomials up to degree N . The results presented in this paper have been
142 obtained with a target mesh that has a polynomial order of $N = 8$. The
143 total number of spectral elements in the mesh is $E = 154 \times 10^3$. The convec-
144 tive terms are advanced in time using an extrapolation of order 3, whereas
145 the viscous terms use a backward differentiation of the same order, resulting
146 in the time-advancement scheme labeled BDF3/EXT3. NEK5000 employs
147 MPI standards for parallelism [26, 27] and parallel computations have been
148 performed on up to 4096 processors. For further details about the spectral
149 elements method, the reader is referred to the books by [28] and [29].

150 The computational domain considered is shown in Figure 2. It is a C-type
151 like mesh, having a total length of $7.08c$ with $c = 2R$, where $R = 1\text{m}$ is the
152 blade radius. It is noted that only the pressure side of the blade is consid-
153 ered in the current work and the turbine rotation is not considered. This is
154 mainly for simplifying the geometry and to avoid the complex, multi scaled

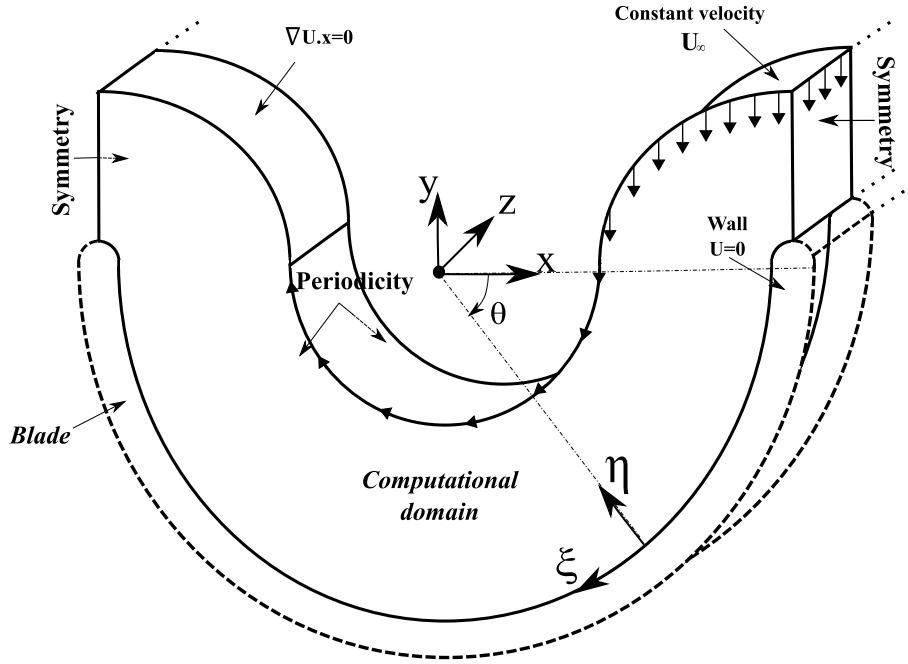


Figure 2: Computational domain and boundary conditions

155 simulation caused by adverse pressure gradient on its suction side that may
 156 also induce massive boundary layer stall. Considering similar studies, the
 157 domain is very large in the wall normal direction ($\eta = 0.4c$) to capture the
 158 flow around the trailing edge, which can experience boundary layer detach-
 159 ments, and it is about 2 times longer in the tangential direction. The span
 160 has been set to $0.2c$ to reduce computational cost. As shown in the result
 161 section, it is sufficient to capture enough characteristic wavelength and to
 162 avoid forcing the flow in the span-wise direction [30].

163 A velocity condition is set at the inlet and for the inner circle. It is given by
 164 $U_\infty = \bar{U} + u'$, where \bar{U} is the magnitude of the mean velocity chosen in order to
 165 match the previous study shown in Figure 1 (i.e. $Re = U_\infty D / \nu = 12.3 \times 10^4$)
 166 with $D = 2c$ being the turbine diameter. As only one blade is considered, the

167 characteristic length is the curvilinear distance between the leading edge and
 168 the trailing edge of the blade. The Reynolds number for the current study is
 169 then $Re_\xi = 9 \times 10^4$. Furthermore, u is a velocity perturbation, which set a
 170 turbulence intensity of 1% at the inlet. It is applied in the code using random
 171 number generation in each cell, leading to the frozen isotropic turbulence of
 172 length scale equal to the cell size at the inlet i.e. $\lambda_t = 0.02m$, whereas no time
 173 correlation is applied. The outlet boundary condition is set as $\nabla \mathbf{U} \cdot \mathbf{x} = 0$.
 174 In order to reduce the CPU time, periodic boundary conditions are imposed
 175 on the vertical side planes of the domain (span-wise direction); whereas a no
 176 slip condition is set on the blade surface.

177

178 Six sets of 37 monitor points at the wall surface are set to record the wall
 179 pressure and friction velocities along the chord. It is equally distributed along
 180 the chord, starting right downstream the leading edge ($\theta = 0^\circ$) with a step
 181 of $\Delta\theta = 5^\circ$, and located respectively at $z = 0.03m$, $z = 0.06m$, $z = 0.09m$,
 182 $z = 0.12m$ and $z = 0.18m$ to capture the spanwise variation of the flow.

183 As shown in Figure 3, mesh refinements are used at the leading edge, the
 184 trailing edge, and in the near wake region. A total number of 385 spectral
 185 elements are set along the chord, whereas the wall normal direction is dis-
 186 cretized with 40 spectral elements and the spanwise direction is composed of
 187 10 elements. It results in a total number of $E = 154 \times 10^3$ spectral elements.

188

189 To verify the mesh convergence, four different element orders are tested,
 190 as depicted in Figure 4. The calculations are first converged in time and
 191 then run for a short time to obtain the averaged values of the forces. The

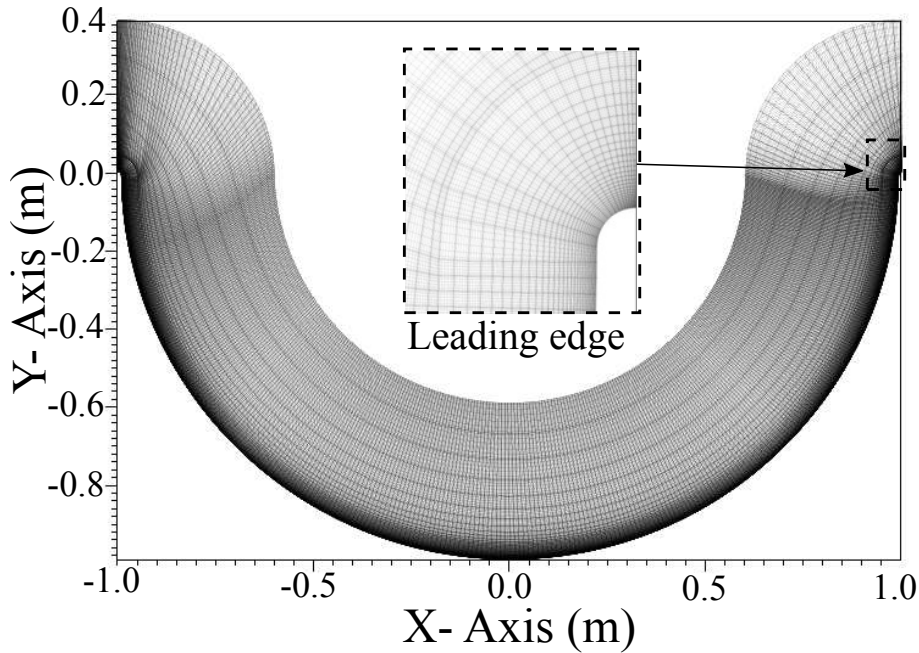


Figure 3: Mesh, $E = 154 \times 10^3$ spectral elements, $N = 8$

192 lowest order mesh does not permit to capture the Görtler modes and is
 193 not sufficient to ensure a DNS accuracy. A relatively low order mesh $N =$
 194 6 ensures DNS calculation in most of the domain, however the wake and
 195 the spanwise wavelength of Görtler modes are not correctly described. The
 196 order mesh $N = 8$ is then necessary to get a full DNS resolution in all the
 197 fluid domain. Finally, increasing the mesh order to $N = 10$ is not affecting
 198 the simulation results. In order to confirm these results quantitatively, the
 199 convergence of the pressure and the viscous components of the lift and drag
 200 forces are presented in Table 1. The viscous components of the lift (Cl_v)
 201 and drag (Cd_v) converge for $N = 6$, whereas it is necessary to use $N = 8$
 202 to obtain a good convergence on their pressure counterparts (Cl_p and Cd_p),

203 and hence the total lift and drag (Cl_t and Cd_t). This confirms that $N =$
 204 8 is necessary to obtain full DNS resolution in the whole computational
 205 domain. Therefore, considering the tradeoff between computational costs
 206 and numerical accuracy, the latter is chosen for the rest of the paper, which
 207 has a final number of 112×10^6 points, leading to $\Delta\xi/\Delta z \approx 0.5$ along 80% of
 208 the wing surface. The boundary-layer mesh is kept constant and the first cell
 209 size has been set in order to obtain $\eta_+ = \eta u_\tau / \nu < 0.2$ along the chord, where
 210 the u_τ is the friction velocity. This will also allow us to investigate higher
 211 Reynolds numbers in the future. Therefore, the main mesh parameters for
 212 the DNS calculation are $\eta_{+,min} < 0.2$, $\xi_{+,min} \approx 1$ and $z_{+,min} \approx 2$ at the blade
 213 surface.

214 The calculation is first initialized with the low order mesh at $N = 6$ in order
 215 to save computational time. After its convergence, the solution is taken as
 216 the initial condition for the higher order mesh at $N = 8$, which in turn is
 217 converged in time after what the calculation is performed the time needed
 218 for the post processing.

219 As shown in Figure 5, the flow instability and the transition to turbulence
 220 is triggered by the blade leading edge, which has a relatively high curvature,
 221 together with the random perturbation at the inlet. This induces a lami-
 222 nar boundary layer detachment right after the leading edge, and a laminar
 223 reattachment at $\theta = 6.3^\circ$. This region is quasi-steady and has small fluctua-
 224 tions that destabilize the flow downstream. The length scale is then fixed to
 225 the surface element size. This is taken as a first step for the present study,
 226 however, a receptivity analysis will be performed in the future, based on the
 227 influence of free stream turbulence.

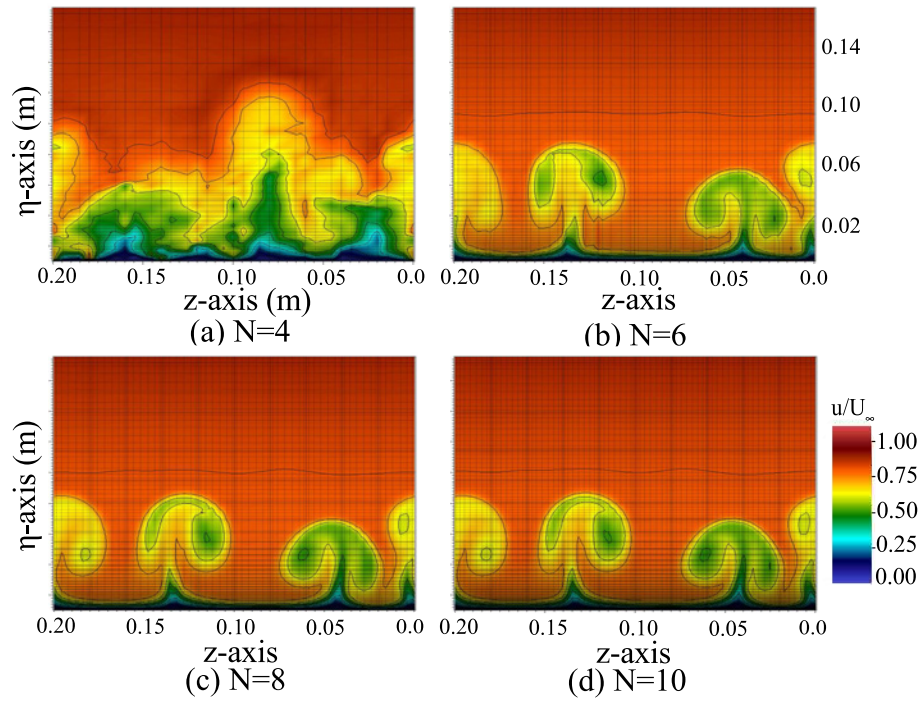


Figure 4: Development of Görtler vortices as a function of element order N

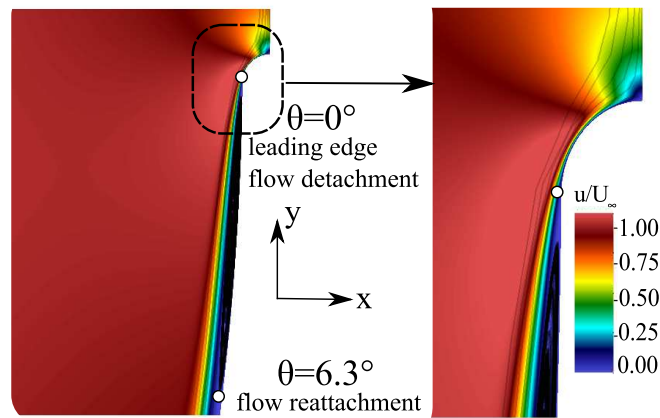


Figure 5: Reversed flow downstream the blade leading edge

| | pressure drag Cd_p | viscous drag Cd_v | total drag Cd_{tot} |
|-------------------------|----------------------|---------------------|-----------------------|
| $N = 10$ | 0.5395 | -0.0021 | 0.5416 |
| $N = 8$ | 0.5392 | -0.0019 | 0.5373 |
| $N = 6$ | 0.5284 | -0.0019 | 0.5266 |
| $N = 4$ (not converged) | 0.5739 | -0.0012 | 0.5727 |
| | pressure lift Cl_p | viscous lift Cl_v | total lift Cl_{tot} |
| $N = 10$ | 0.0190 | -0.0078 | 0.0113 |
| $N = 8$ | 0.0194 | -0.0077 | 0.0117 |
| $N = 6$ | 0.0147 | -0.0076 | 0.0071 |
| $N = 4$ (not converged) | 0.0349 | -0.0080 | 0.0269 |

Table 1: Comparison lift and drag coefficients for different spectral element order N .

228 3. Validation study

The Savonius blade calculation is first validated on a simple concave curved wall, where a reference study based on an equivalent DNS using finite volume algorithm is available in the literature [16]. The goal is to show the ability of the current method to capture the centrifugal instabilities. Therefore, only in this section, a domain size with a spectral element mesh identical to [16] is considered and is shown in Figure 6. The quarter of a circle with the radius of $R = 1\text{m}$ and thickness of $\eta = 0.1\text{m}$ is defined as in [16]. This lead to $\xi_+ = 1500$ and $\eta_+ = 100$ for the non dimensional stream-wise and wall normal directions. To optimize the computational time, the span is reduced to $L_z = 0.05\text{ m}$ compared to $L_z = 0.0892$ in [16]. This is found to be enough to capture at least 5 mushroom structures in the span-wise direction, compared to 9 in the reference study. The number of spectral element is $N_\xi = 120$, $N_\eta = 20$ and $N_z = 10$ with order 8, leading to a total of 12×10^6

points, compared to 17×10^6 in the reference study due to a smaller span of the present domain. The details of the mesh parameters are given in Table 2. A Blasius profile with an external velocity of $U_\infty = 2.8\text{m/s}$ and a thickness of $\delta=0.00373\text{ m}$ is defined at the inlet. A random perturbation equivalent to the blade calculation is also defined with a turbulence intensity of about 1%. $U_\infty = 2.8\text{m/s}$ is also set at the upper wall, leading to a maximum Reynolds number of $Re_\xi = 28.2 \times 10^4$, which induces laminar to turbulent transition and fully turbulent flow over more than 60% of the domain. Other boundary conditions are identical to those presented in section 2.

The space and time averaged wall friction coefficient is first compared with

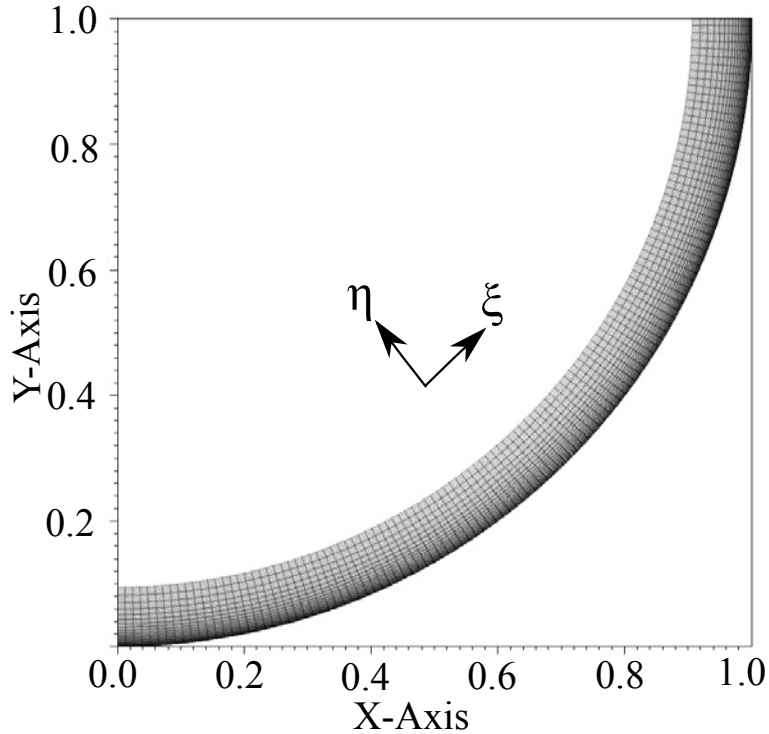


Figure 6: Spectral element mesh for the curved wall, number of element $E = 24 \times 10^3$

the DNS of [16] and the experiments of [31]. In addition, the laminar and turbulent solutions for a flat plate are shown. The wall friction inside the laminar region compares well with the previous DNS and the experiment. The level of friction follows the laminar flat plate solution, as there is no development of centrifugal instability in this region. The friction coefficient increases earlier in the measurement of [31] compared to both DNS simulations. This is due to the experimental set up at the inlet of the test section that consider series of 12 perturbation wires with constant spacing. This tends to force the inception of centrifugal instabilities, which causes early transition in the boundary layer. It can be seen than both DNS capture the transition at the same location, and the level of wall friction inside the turbulent boundary layer agree well, where higher values are obtained compared to the turbulent flat plate solution.

The development of Görtler instability is shown in Figure 8. The same boundary layer thickness is observed in Figure 8(a), and the inception of longitudinal streaks is equivalent to that of [16]. Because the inlet perturbation is different between the two computations, the streaks are organized slightly differently, however, the overall wall normal development and span-wise wavelength match very well. In particular, the distinct behavior between isolated mushrooms and merging mushrooms developments are reproduced by the present DNS.

The evolution of the local Görtler number, represent the ratio between destabilizing centrifugal to stabilizing viscous forces, and two boundary layer velocity profiles are then compared in Figure 9. The Görtler number is based on the boundary layer momentum thickness θ_t , the radius R , the upstream

| | span L_z (m) | N_ξ - N_η - N_z | total grid points | Δ_ξ^+ - Δ_η^+ - Δ_z^+ |
|------------------------|----------------|----------------------------|-------------------|---|
| present DNS | 0.05 | 960-160-80 | 12×10^6 | 16.8-0.56-6.42 |
| Schrader et al. (2011) | 0.0892 | 1025-129-129 | 17×10^6 | 15.7-0.7-7.1 |

Table 2: comparison of mesh resolution, present DNS vs DNS of Schrader et al. (2011)

velocity U_∞ and the kinematic viscosity ν , and is defined as:

$$G_{\theta_t} = \frac{U_\infty \theta_t}{\nu} \sqrt{\frac{\theta_t}{R}}. \quad (2)$$

229 In Figure 9 (a), both DNS first match with the laminar flat plate solution.
 230 Around $\xi_+ = 400$, $G_\theta = 8$, the inception of longitudinal streaks increases the
 231 Görtler number due to an increase of the momentum thickness; both DNS
 232 match very well and go away from the laminar flat plate solution. Finally,
 233 the Görtler number of the present DNS is lower than the DNS of [16] from
 234 the breakdown region (around $\theta = 35^\circ$), and keep lower values until the
 235 end of the fluid domain. This difference can be attributed to (i) differences
 236 in the space-time averaging due to development of highly three dimensional
 237 flow, and (ii) because of the influence of inlet perturbation that modifies the
 238 breakdown of streaks.

239 Two boundary layer velocity profiles are also compared in Figure 9 (b). At
 240 $\theta = 33.7^\circ$, the flow is governed by the Görtler streaks and both velocity
 241 profiles are highly inflectional, which is captured by the present DNS. Down-
 242 stream, the boundary layer is fully turbulent, and a minor difference is ob-
 243 served between the two computations.

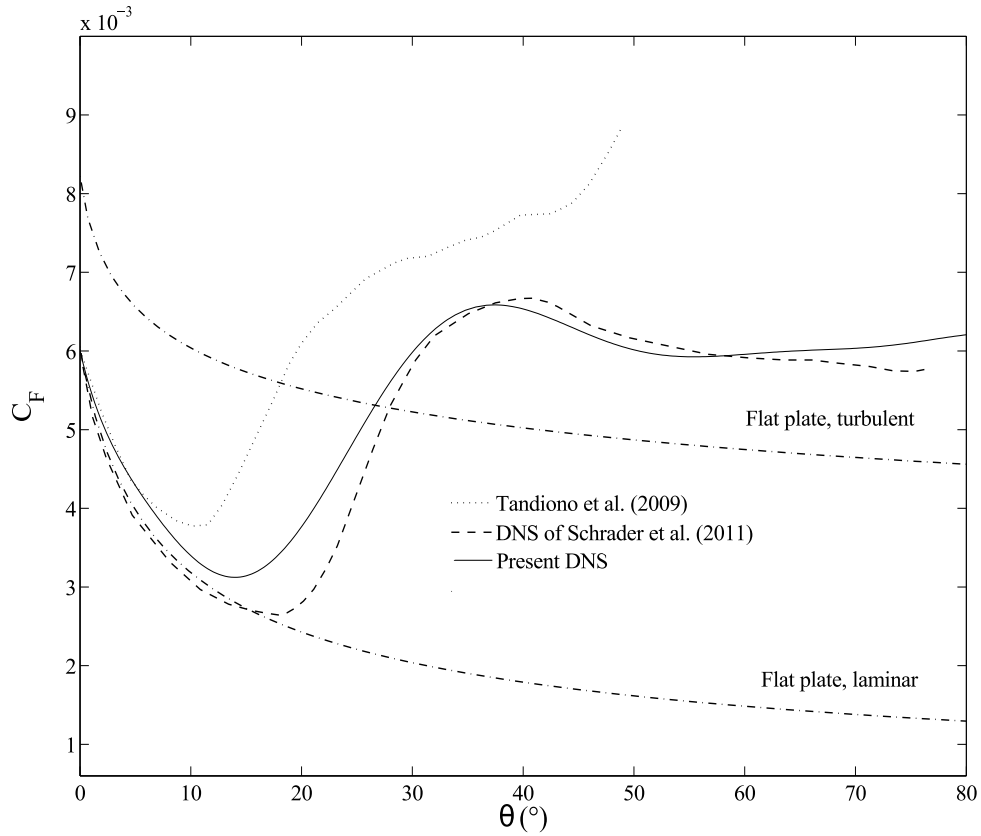


Figure 7: Comparison of the spanwise and time averaged wall friction coefficient along the curved plate; present DNS vs DNS of Schrader et al. (2011) and experiments of Tandiono et al. (2009)

244 4. Results and discussions

245 The iso surface of λ_2 criterion colored with contour of velocity is shown in
 246 Figure 10. Long streamwise vortices are first observed around $\theta = 40^\circ$. It is
 247 characterized by streaks that are clearly characteristic of Görtler modes in-
 248 ception. These streamwise elongated structures break down (approximately
 249 around $\theta \approx 100^\circ$) because of secondary instabilities. Their developments are

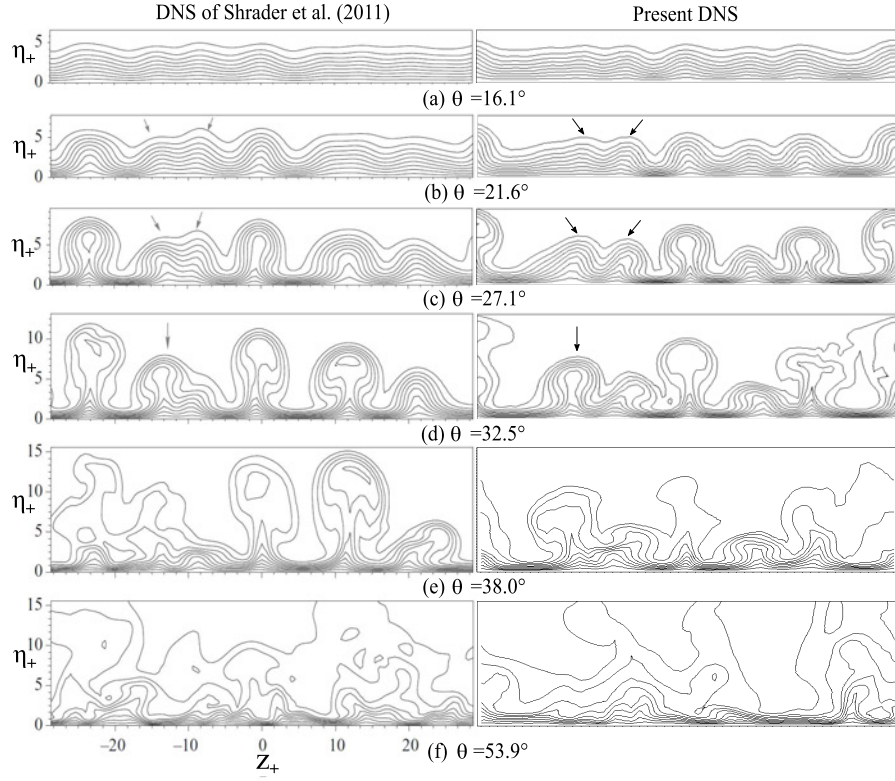


Figure 8: Development of Görtler instability. Velocity profiles for different angles θ ; present DNS vs DNS of Schrader et al. (2011)

250 characterized by the appearances of typical horseshoe vortical structures.
 251 The flow then extend in the wall normal direction and smaller scales vortices
 252 are observed, which are identified as sinuous streaks. These streaks are ob-
 253 served up to the transition process, around $\theta = 170^\circ$, where the flow becomes
 254 fully turbulent.

255

256 Figure 11 shows the instantaneous evolution of boundary layer flow and
 257 the corresponding boundary layer thickness. It is taken at $z = 0.06$, where a
 258 classical mushroom structure develops. A laminar boundary layer develops

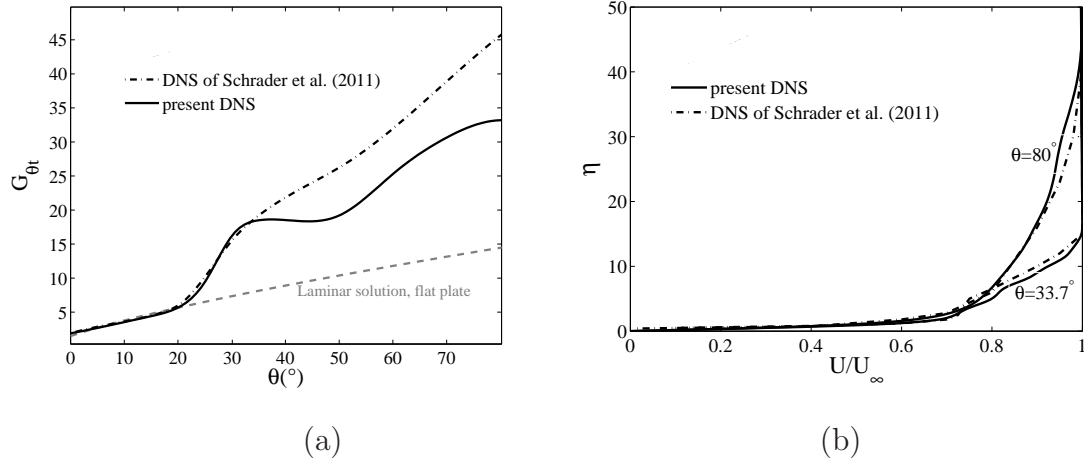


Figure 9: Validation of (a) Local Görtler number and (b) Mean velocity profiles (temporal spanwise average).

259 from the leading edge of the blade, and reaches to its maximum thickness
 260 before the inception of Görtler vortices. When streaks appear, the boundary
 261 layer thickness starts to stagnate (Figure 11 (b)), whereas the low speed
 262 region suddenly increases due to the presence of streaks (Figure 11 (a)). With
 263 the development of secondary instabilities, periodic structures are observed
 264 in the stream-wise direction, until the flow transition to turbulence near the
 265 trailing edge, highlighted by higher velocities.

266 To demonstrate that the centrifugal instabilities are correctly captured, the
 267 evolution of Görtler number is shown in Figure 12. At first, the present DNS
 268 calculation match the typical values for a laminar boundary layer (where
 269 $\theta_t = 0.664/\sqrt{Re}$). A sudden increase is observed around $G_{\theta_t} = 8$ at $\theta = 40^\circ$,
 270 which is the typical value where the Görtler vortices appear, also observed
 271 for example in [18] and [16]. The DNS solution doesn't match anymore with
 272 the laminar solution for a flat plate, since the flow becomes three-dimensional

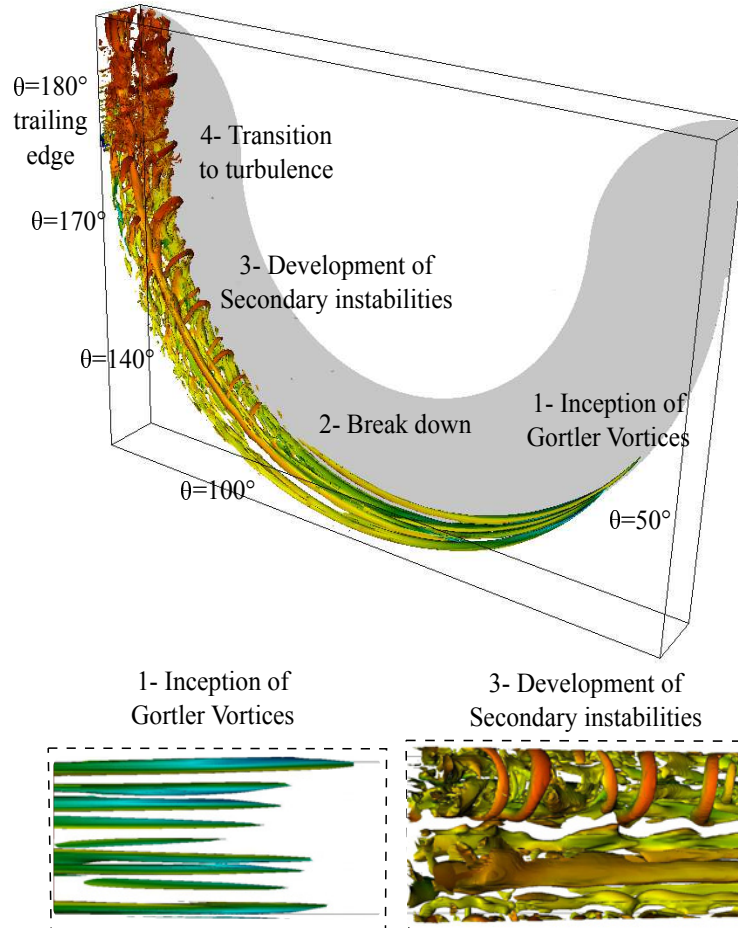
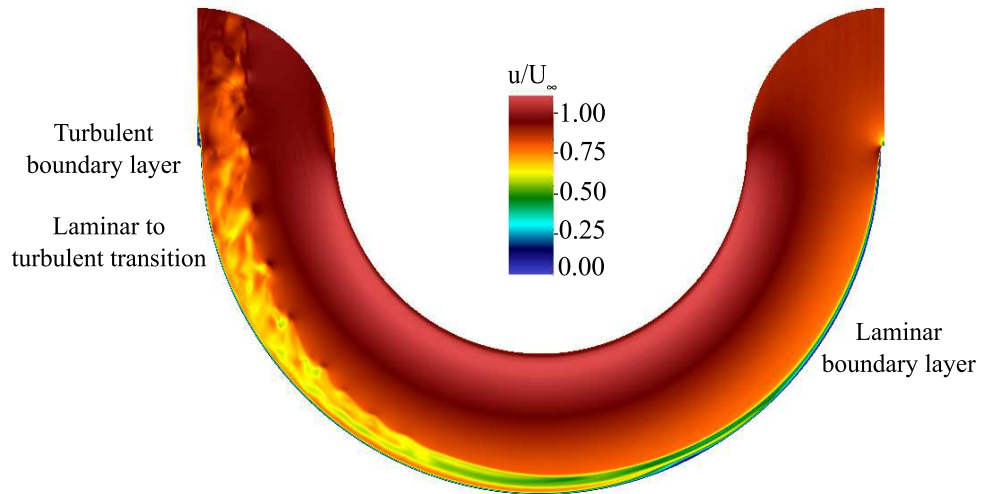


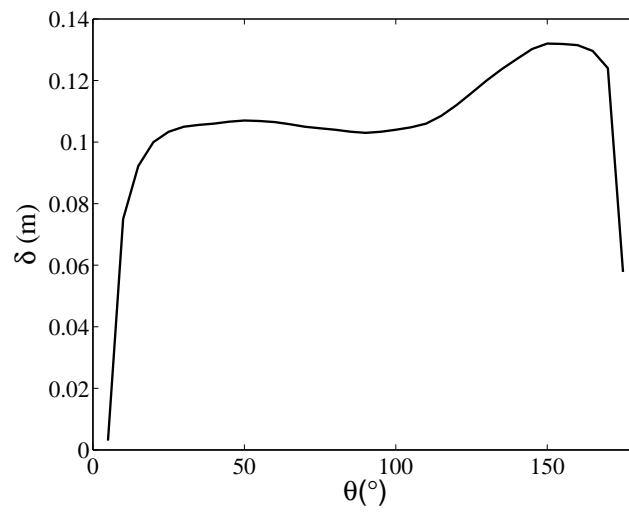
Figure 10: Coherent structure at the blade surface, iso surfaces of λ_2

273 where a progressive transition to turbulence occurs.

274 Figure 13 shows the variation of the velocity magnitude in the (z, η) plane.
 275 Streaks are seen in the first stage of the physical mechanism, with the wave-
 276 length enforced by the inflow conditions. The first span-wise modulation is
 277 observed at $\theta = 30^\circ$ (Figure 13 (a)). The streaks then develop in the wall
 278 normal direction and form low speed streaks (Figure 13 (b)) that progres-



(a)



(b)

Figure 11: (a) Velocity field in the (ξ, η) plane, (b) boundary layer thickness, $z = 0.06\text{m}$

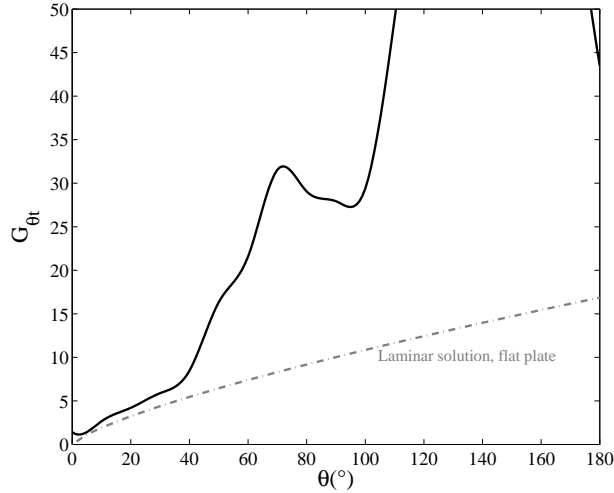


Figure 12: Variation of the Görtler number along the blade chord

279 sively form mushroom structures (Figure 13 (c)). Since the wavelength is
 280 relatively small compared to the mushroom overall size, the structures com-
 281 pete with each other. As a consequence, the structures close to each other
 282 are merging whereas they continue to develop in the wall normal direction
 283 (Figure 13 (b) to (d)). At this stage, the wavelength reaches a periodic state,
 284 which are directly related to the Reynolds number. In Figures 13 (e) to (g)
 285 two distinct behavior are observed. The right side of the domain shows a
 286 characteristic mushroom development, where the upper structure moves in
 287 the wall normal direction and detaches, after what multi-scale structures are
 288 observed. The left side mushroom competes again with another mushroom
 289 structure and merges during the development, which keep larger coherent
 290 structures and maintain the laminar flow. This is also highlighted by Fig-
 291 ure 10. This behavior seems consistent with the validation case, where faster
 292 transition to turbulence was observed with less variations of the physic in the

293 span-wise direction. This is mainly because the Reynolds number is lower for
 294 the blade case, combined with a longer domain size in streamwise direction
 295 that includes development of a Görtler flow in a lower speed condition.

296

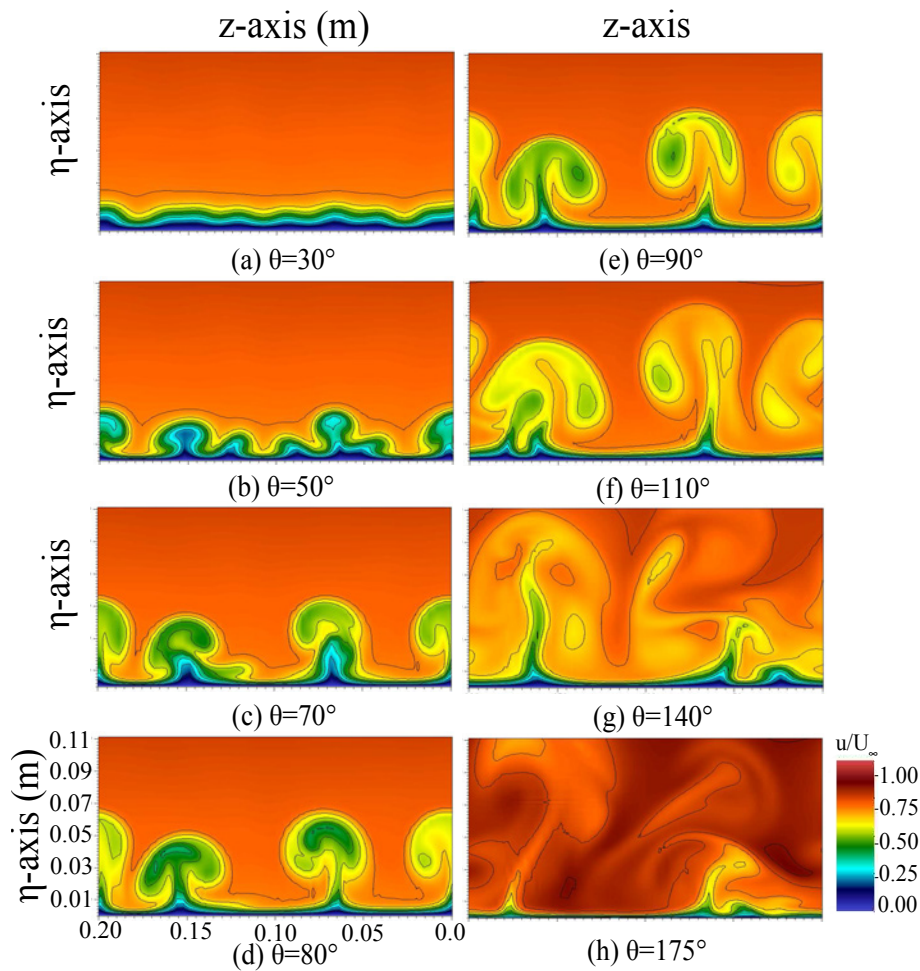


Figure 13: Contour of velocity magnitude in the (z, η) plane

297 To get a full observation on the development of Görtler flow throughout
 298 the domain, slices in the (ξ, η) plane are shown in Figure 14. Near the wall

299 (Figure 14 (a)), the low velocity field illustrates the merging of longitudinal
 300 streaks formed by the inlet perturbation after $\theta = 40^\circ$. A second merging
 301 occurs from $\theta = 45^\circ$ and creates a large laminar streak. It can be seen in
 302 this contour plot that the Görtler flow is mainly directed in the streamwise
 303 direction. In Figure 14 (b), inception of mushroom like structures is visi-
 304 ble, highlighted by the green velocity field. First spanwise disturbances are
 305 observed around $\theta = 110^\circ$, which is the beginning of the transition process.
 306 Near the trailing edge, the Görtler flow develop in the wall normal and span-
 307 wise directions with high velocity field (Figure 14 (c)), where turbulence is
 observed.

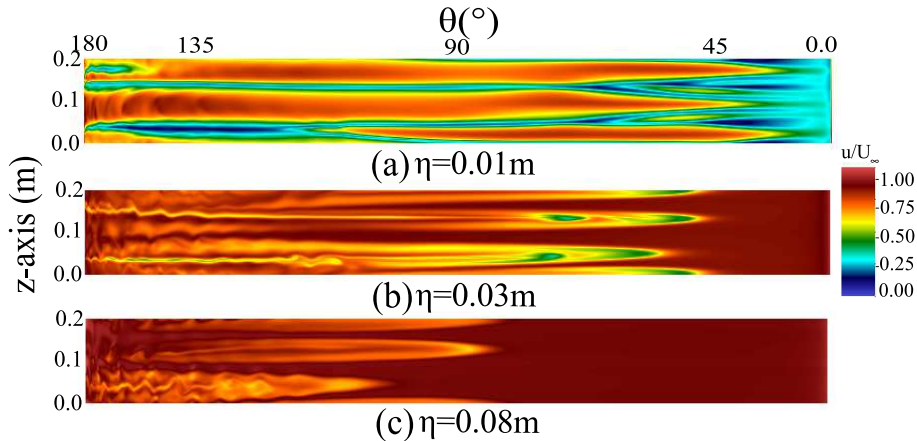


Figure 14: Contour of velocity magnitude in the (ξ, η) plane

308

309 The stream-wise skin friction coefficient, $C_{F\xi} = \tau_{\xi}/(0.5\rho U_{\infty}^2)$, as func-
 310 tion of Re_{ξ} is shown in Figure 15 for three different z locations, and for the
 311 span-wise averaged case. Here τ_{ξ} is the wall shear stress caused by flow in
 312 stream-wise direction and is calculated from the monitoring points placed at
 313 the cells adjunct to the wall. After obtaining the convergence, each point

314 is time averaged over the whole simulation period. This Figure shows the
 315 resulting mean value in continuous black line, as well as the minimum and
 316 maximum values in dotted lines, which highlights the fluctuations. It is also
 317 compared with the flat plate solution, for both laminar and turbulent bound-
 318 ary layer flows. First, Figure 15 (a) shows the evolution of the wall friction at
 319 the location where the mushroom-type structure develops and breakdown to
 320 turbulence occurs (i.e. $z = 0.06\text{m}$). Because of the small reversed flow area
 321 downstream of the leading edge, negative value of the skin friction coefficient
 322 is observed. The behavior is fully steady, and it reaches the friction level close
 323 to the laminar boundary layer around $Re_\xi = 2 \times 10^4$, i.e. $\theta = 20^\circ$. When
 324 the Görtler vortices appear at $Re_\xi = 2 \times 10^4$ or equivalently as $\theta = 40^\circ$, the
 325 friction coefficient suddenly increases and stays steady. Fluctuations appear
 326 in the breakdown region (around $Re_\xi = 5 \times 10^4$), and increase up to the
 327 transition to turbulence near the trailing edge, where the friction reaches a
 328 level close to the turbulent boundary layer for the flat plate.

329 Figures 15 (b) and (c) show different behaviors. At these locations (i.e.
 330 $z = 0.012\text{m}$ and $z = 0.018\text{m}$), there is competition and merging of two
 331 mushroom structures, which largely increases the wall friction (see in the
 332 range $20 \times 10^4 < Re_\xi < 5.5 \times 10^4$). Since the coherent structures are larger
 333 up to the trailing edge, the level of friction is higher in the transitional region.
 334 Finally, the span-wise averaged friction coefficient in Figure 15 (d) appears to
 335 be higher than the typical value for a turbulent boundary layer. The reasons
 336 are the development of Görtler flow, combined with mushroom merging that
 337 increases the wall friction.

338 To highlight the development of three-dimensional flow together with sec-

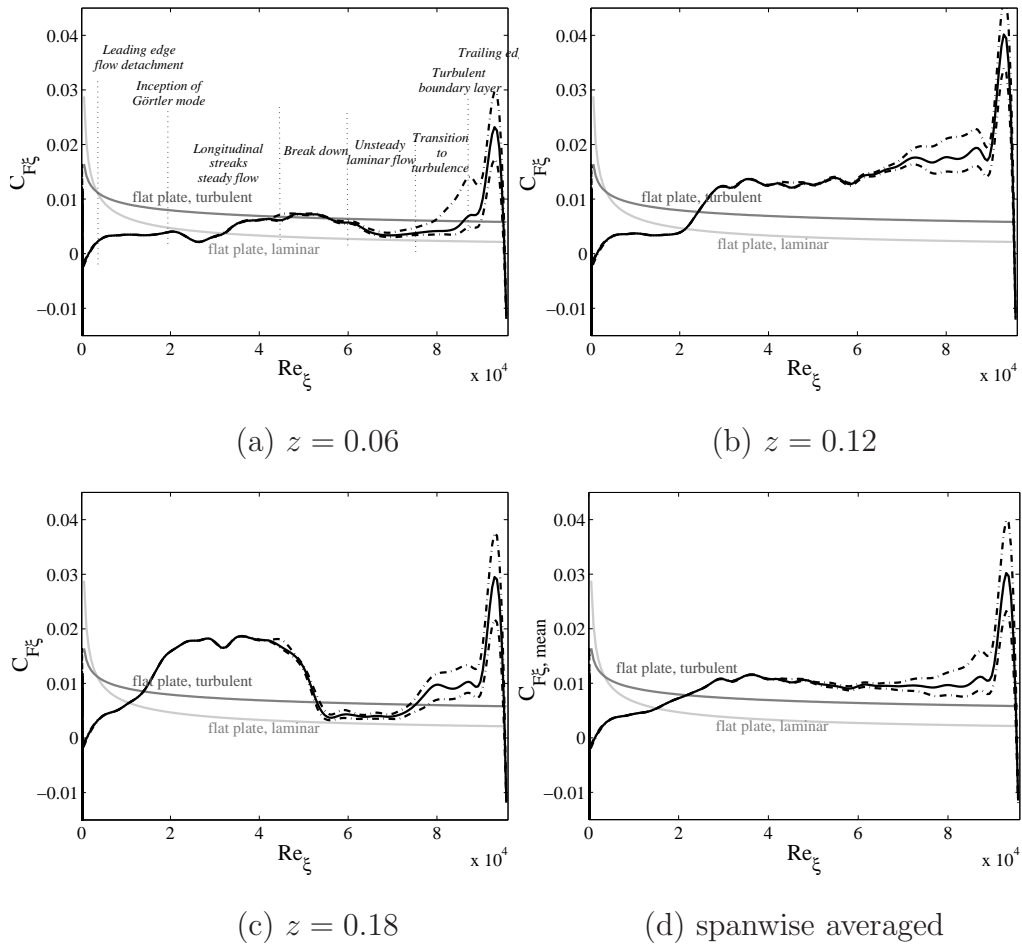


Figure 15: Time averaged stream-wise friction coefficient along the blade chord. (-) mean values, (-.) fluctuations.

339 ondry instabilities, the time averaged skin friction coefficients in the span-
 340 wise direction $C_{Fz} = \tau_z / (0.5\rho U_\infty^2)$ are plotted in Figures 16 (a) to (c) for
 341 the three span locations, and for the span-wise averaged case in Figures 16
 342 (d). Here τ_z is the wall shear stress caused by flow in the span-wise direc-
 343 tion. Large span-wise fluctuations are clearly observed from the inception
 344 of Görtler mode, which are representative of development and breakdown
 345 of longitudinal streaks, and the establishment of turbulent flow. The re-
 346 sults highlight fluctuations from the breakdown region, where the flow be-
 347 comes three dimensionnal around $\theta = 120^\circ$. Larger fluctuations are observed
 348 after the breakdown of the longitudinal streaks, where the flow becomes
 349 highly unsteady and three dimensional (Figure 16(a) between approximately
 350 $120^\circ < \theta < 180^\circ$). The spatially averaged value in Figure 16 (d) is close
 351 to zero with symmetric fluctuations, however, more points in the span-wise
 352 direction would be necessary to reach a complete balance (i.e. net 0 value).

353

354 Details of horseshoe like structures are shown in Figure 17, where the
 355 iso λ_2 with contour of the stream-wise vorticity are plotted in the unsteady
 356 region of $120^\circ < \theta < 160^\circ$. Opposite vorticity levels are observed on the
 357 two sides the sinuous streaks in the span-wise direction, which clearly help
 358 for the development and stretching of mushroom structures along the η axis,
 359 until their detachment. This behavior is initiated by a pair of contra rotative
 360 vortices that take place in the core of the mushroom structure and help the
 361 inception of secondary instability. When the structure develops, vorticities
 362 progressively mix together and smaller structures appear in the core, which
 363 is the first stage of transition to turbulence. It then produces the breakdown

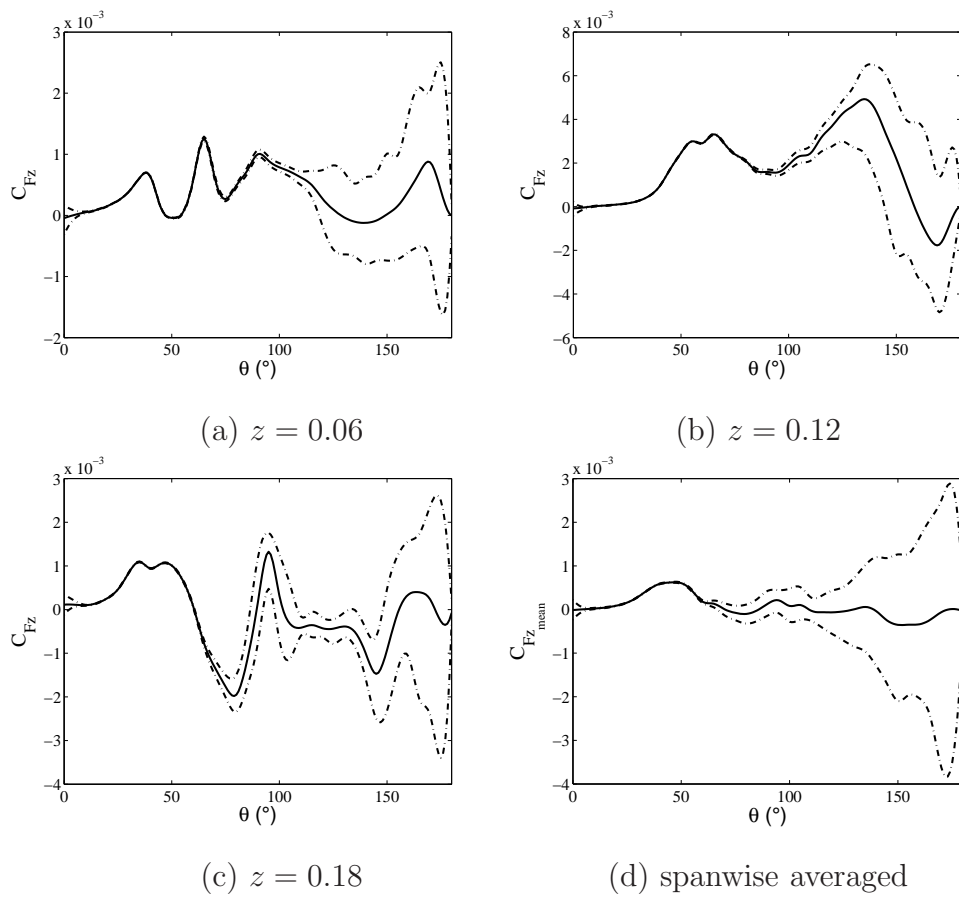


Figure 16: Time averaged spanwise friction coefficient along the blade chord. (-) mean values, (-.) fluctuations.

364 of secondary structures and hence laminar to turbulent transition occurs.

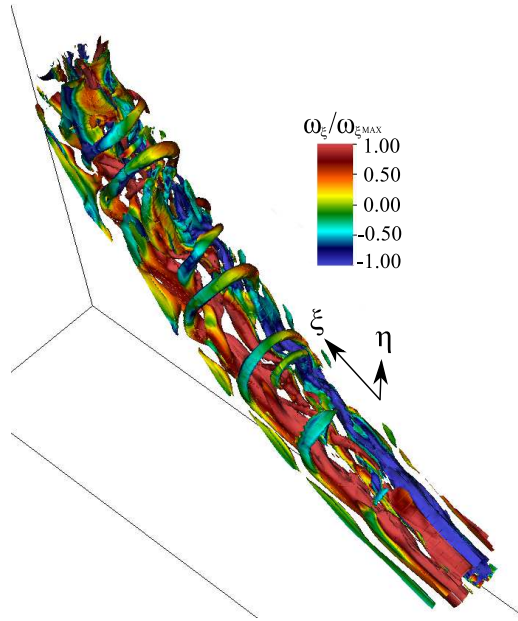


Figure 17: Detail of secondary instability, iso λ_2 and streamwise vorticity contour plots

365 To demonstrate the effect of centrifugal instabilities and the modification
 366 of the boundary layer regime caused by laminar to turbulent transition, on
 367 the blade performance, the DNS results are compared with three-dimensional
 368 URANS computation performed with the commercial software STARCCM+.
 369 The exact same computational domain is defined in the URANS solver. This
 370 allows to directly quantify the influence of centrifugal instabilities on the
 371 boundary layer flow and forces on the blade. It is discretized with unstruc-
 372 tured polyhedral, whereas a structured mesh is defined in the boundary layer
 373 region with low Reynolds resolution, leading to $\eta_+ = 1$. The total number of
 374 cells are $N = 839 \times 10^3$, which is found to be sufficient to fully solve for the
 375 boundary layer flow. A detailed space and time convergence study of flow

376 past savonius turbine blades using URANS based code is presented in [14].
377 The same boundary conditions are imposed, except for the inlet where no
378 perturbation is set. The $k-\omega$ SST turbulence model is chosen, which leads
379 to fully turbulent boundary layer over the blade. The time step has been
380 selected in order to achieve $CFL = u\Delta t/\Delta x$ less than or equal to 1 in the
381 entire domain, and a second order backward Euler scheme has been chosen.
382 First, the time average flow fields for the DNS and URANS computations
383 are shown in Figure 18. It is noted that the flow in URANS calculation is
384 already averaged by the turbulence model. The URANS computation does
385 not predict the centrifugal instability and the development of mushroom like
386 structures, which lead to quasi stationary flow in the fluid domain. The de-
387 velopment of Görtler flow significantly increases the low speed region near
388 the wall, up to the trailing edge of the blade. This can strongly modify the
389 trailing edge vortex that plays an important role in the vortex shedding pro-
390 cess of the turbine, and hence influences its overall performances.

391 The pressure and friction coefficients along the chord are shown in Figure
392 19. The absolute pressure level for URANS calculation is globally higher
393 than its DNS counterpart. The two solutions are close to each other up to
394 the breakdown of longitudinal streaks. When the flow gets unsteady and
395 transitional for the DNS, the URANS calculation over-predict the pressure
396 coefficient, which shows a maximum difference of about $C_P = 0.2$ near the
397 trailing edge. As far as the DNS solution is concerned, very few fluctuation
398 is observed in the laminar region, whereas a maximum level of fluctuation
399 is found in a region where the longitudinal streaks breakdown (*i.e.* between
400 $\theta = 80^\circ$ to $\theta = 100^\circ$). The mechanism of breakdown obviously induces a

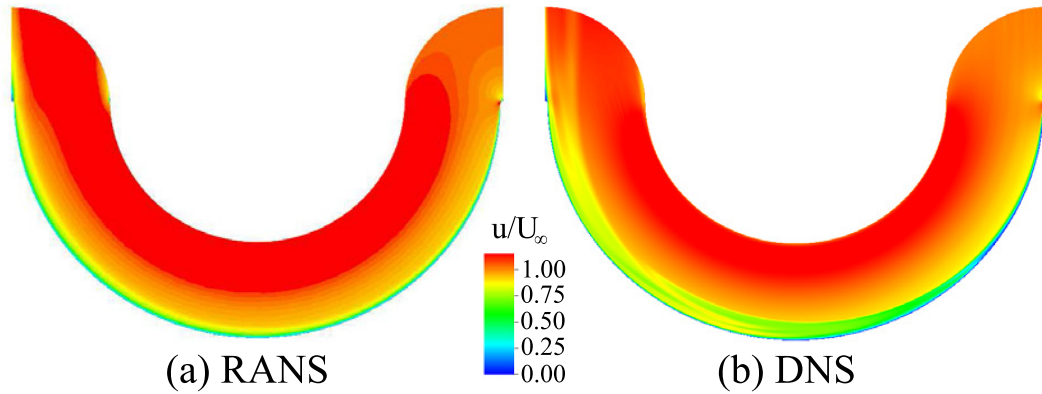


Figure 18: Velocity field in the (ξ, η) plane for $z = 0.06$, comparison between URANS and DNS solutions.

401 strong and localized pressure jump. The fluctuations are then almost con-
 402 stant, whereas the average pressure coefficient presents a constant slope along
 403 80% of the chord. As shown in Figure 1, a positive pressure coefficient on
 404 the returning blade produces a drag that act positively on the axis moment
 405 of the turbine, used in the energy conversion. Hence, its variation may di-
 406 rectly influence the turbine power. The friction coefficient is very different
 407 for the two solutions. The reversed flow region near the leading edge induces
 408 negative friction coefficient for the DNS, whereas it is not predicted by the
 409 URANS based code. From the development of Görtler flow, the average fric-
 410 tion coefficient predicted by DNS is almost two times higher than that of the
 411 URANS solution. This high level of shear is due to the development and the
 412 breakdown of longitudinal streaks in the DNS, compared to fully attached,
 413 turbulent boundary layer in the URANS calculation.

414

415 The time average lift and drag coefficients obtained for the URANS and

416 DNS calculations are shown in Table 3. The lift and drag coefficients are de-
 417 fined as $Cl = L/(0.5\rho U_\infty^2 c \times b)$ and $Cd = D/(0.5\rho U_\infty^2 c \times b)$, where $c = 2R$, b ,
 418 L and D are, respectively, the chord, the span, the lift and drag forces. As ob-
 419 served in this table as well as in Figure 19, the pressure drag presents a small
 420 variation because the larger pressure difference occurs near the trailing edge,
 421 where the surface normal is perpendicular to the drag. As a consequence, the
 422 pressure lift coefficient Cl_p is more affected, where $Cl_p = 0.02570$ is obtained
 423 for the URANS solution against $Cl_p = 0.0194$ for the DNS solution. The
 424 viscous drag is, however, strongly modified between the DNS and URANS
 425 solutions. After $\theta = 90^\circ$, the high shear region associated with the devel-
 426 opment of longitudinal streaks, the breakdown and transition to turbulence
 427 increases the positive viscous drag. This significantly decreases the total drag
 428 which is oriented negatively. The viscous drag coefficient $Cd_v = 0.00041$ is
 429 obtained for the URANS solution against $Cd_v = -0.0019$ for the DNS solu-
 430 tion, which is three times more than that of the URANS solution and is in
 431 opposite direction. Therefore, it is clear that although URANS gives a good
 432 initial estimation SSWTs, DNS may be necessary to investigate the detailed
 433 flow physics and complex three-dimensional phenomena for such problems.
 434 Moreover, even if the differences in the total forces are weak in the present
 435 case, the authors believe that higher Reynolds numbers can induce signifi-
 436 cant differences in the performances due to larger transitional zone along the
 437 blade.

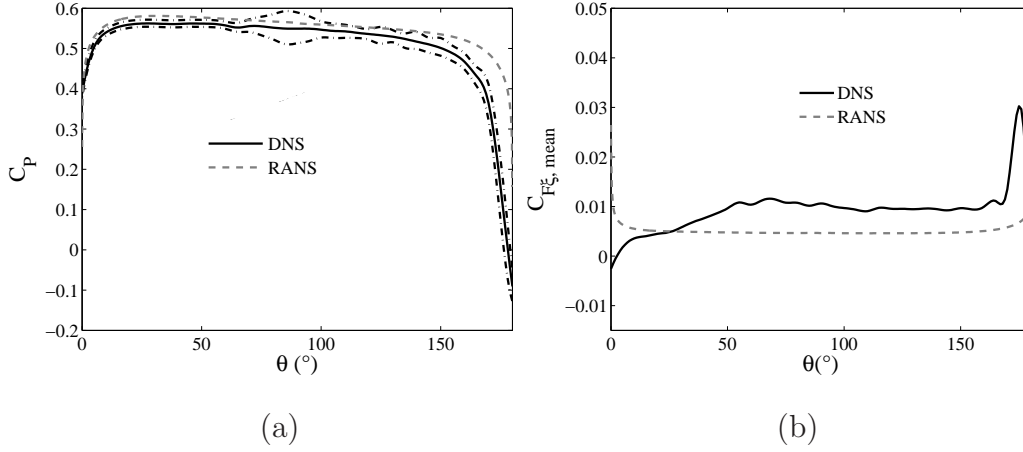


Figure 19: Comparison of the time averaged pressure and friction coefficient along the blade chord for the URANS the DNS solutions. (a) show the (-) mean values, (-.) fluctuations for the DNS solution.

| | pressure drag Cd_p | viscous drag Cd_v | total drag Cd_{tot} |
|-------|----------------------|---------------------|-----------------------|
| URANS | 0.55596 | 0.00041 | 0.55637 |
| DNS | 0.5392 | -0.0019 | 0.5373 |
| | pressure lift Cl_p | viscous lift Cl_v | total lift Cl_{tot} |
| URANS | 0.02570 | -0.00584 | 0.01990 |
| DNS | 0.0194 | -0.0077 | 0.0117 |

Table 3: Comparison lift and drag coefficient for the URANS and DNS solutions.

438 5. Conclusion

439 In this paper, DNS calculations were performed to capture flow insta-
440 bilities over the pressure side of a vertical axis Savonius-style wind turbine
441 (SSWT). The flow domain is simplified in order to lead a DNS accuracy for
442 a maximum Reynolds number of $Re_\xi = 9 \times 10^4$. It is clear from this work
443 that centrifugal instabilities occur along the blade, and trigger the boundary
444 layer transition, which has not yet been considered in researches involving
445 the improvement of SSWT performances.

446 It is observed that the boundary layer flow experiences classical centrifugal
447 instabilities around the mid chord of the blade, where longitudinal streaks de-
448 velop. The streaks then breakdown when secondary instabilities occur. The
449 flow then governs by mushroom like structures followed by boundary layer
450 transition to turbulence. Because of the relatively low Reynolds number in-
451 duced by the small scale of the turbine, the mushroom structures occurring
452 in the Görtler flow can compete with each other and maintain the laminar
453 flow. The results show that this particular physic induces a significantly
454 higher friction coefficient from the inception and, break down of the Görtler
455 vortices until transition to turbulence.

456 The comparison with fully turbulent URANS calculation shows that the de-
457 velopment of Görtler flow highly modify both the pressure and friction at
458 the wall, which in turn modifies the viscous components of the drag and
459 lift forces. It is noted that although several simplifications are made in the
460 current DNS, the computational costs are still significant even when com-
461 pared with the full domain URANS simulations. Nevertheless, unlike DNS,
462 URANS cannot predict (i) the reverse flow at the leading edge, due to the

463 fully turbulent flow hypothesis, (ii) the development of centrifugal instabili-
464 ties as well as (iii) the thickness of low speed region near the wall. While the
465 latter affects the trailing edge vortex and its consequence shedding that in-
466 directly modify the turbine performance mainly by altering the reverse flow
467 on the second blade, the two formers directly touch pressure and friction
468 coefficients calculation. As examples, DNS shows (i) a negative friction co-
469 efficient at the leading edge, (ii) an average friction coefficient that is two
470 times higher than URANS and (iii) a maximum difference of about $C_p = 0.2$
471 in the pressure coefficient. It is also observed that the low speed region is
472 highly increased in the DNS up to the trailing edge, which can strongly in-
473 fluence the well-known mechanism of trailing edge vortex shedding on the
474 returning blade, which partially form the wake flow. Therefore, the accuracy
475 reached by DNS along with the lack of data in the literature, necessitates the
476 existence of the current work to provide more reliable data for such simple
477 yet important geometry.

478 To the authors best knowledge, it is the very first attempt to perform DNS
479 over a blade turbine, and to demonstrate that centrifugal instability can oc-
480 cur on this kind of turbine. Even if very strong hypothesis has been taken,
481 including no blade rotation, no suction side and constant velocity profile at
482 the inlet; the results presented in this paper can help in the SSWT design
483 and developments. The direct application to this study remains in the pre-
484 diction of static performance, which determine the self starting capability
485 of the turbine. More generally, as very few DNS studies were considered in
486 the analysis of Görtler flow, this paper is also addressed to the centrifugal
487 instability community.

488 Possible extension of this study concerns the set up of realistic velocity pro-
489 file at the inlet of the domain. This includes the implementation of isotropic
490 turbulence models such as von-Kármán model, and the set up of mean ve-
491 locity profiles that reproduces the gap flow between the blades, in particular
492 for the leading edge flow detachment. To characterize these aspects, the in-
493 vestigation of the receptivity on the Görtler flow and transition mechanism
494 would be necessary. Moreover, even if taken into account the full case of
495 the turbine in rotation is not possible through DNS, the constant increase
496 of computational power will allows to consider a more realistic case, such
497 as simulating the flow over a full turbine blade, and increase the Reynolds
498 number to investigate the performances for various operating conditions.

499

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Direct Numerical Simulation is performed on a Savolius Style Wind Turbine blade

A high order spectral element method is used

Centrifugal instability occurs at the pressure side of the blade

The break down of Görtler vortices cause the flow to transit to turbulence

The pressure and friction distributions along the blade are altered by the transition phenomena